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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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☑ *Additional inventors are being named on the 1 separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

ELECTRO-OPTICAL TOW-BY-TWO SWITCHING IN A PHOTONIC BANDGAP WAVEGUIDED COUPLER

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ENCLOSED APPLICATION PARTS *(check all that apply)*

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☑ Drawing(s) *Number of Sheets* 2 ☐ Other (specify)

☐ Application Data Sheet. See 37 CFR 1.76

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Respectfully submitted,

SIGNATURE James M. Olsen

Date 01 / 22 / 02

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Docket Number: 131*288

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PROVISIONAL APPLICATION COVER SHEET
Additional Page

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Number 1 of 1

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PATENT
Attorney Docket No.131*288

UNITED STATES PROVISIONAL PATENT APPLICATION

of

Dennis W. PRATHER, Ahmed SHARKAWY, Shouyuan SHI, and Richard A. SOREF

for

ELECTRO-OPTICAL TWO-BY-TWO SWITCHING IN A PHOTONIC BANDGAP WAVEGUIDED COUPLER

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BACKGROUND OF THE INVENTION

A. Field of the Invention

The present invention relates generally to photonic crystals, and, more particularly to electro-optical two-by-two ("2x2") switching in a photonic bandgap waveguided coupler.

B. Description of the Related Art

During the last decade photonic crystals (also known as photonic bandgap or PBG materials) have risen from an obscure technology to a prominent field of research. In large part this is due to their unique ability to control, or redirect, the propagation of light. **E. Yablonovich, "Inhibited spontaneous emission in solid-state physics and electronics," *Physical Review Letters*, vol. 58, pp. 2059-2062 (May 1987), and S. John, "Strong localization of photons in certain disordered dielectric superlattices," *Physical Review Letters*, vol. 58, pp. 2486-2489 (June 1987)**, initially proposed the idea that a periodic dielectric structure can possess the property of a band gap for certain frequencies in the electromagnetic spectra, in much the same way as an electronic band gap exists in semiconductor materials. This property affords photonic crystals with a unique ability to guide and filter light as it propagates within it. Thus, photonic crystals have been used to improve the overall performance of many optoelectronic devices.

The concept of a photonic band gap material is as follows. In direct conceptual analogy to an electronic band gap in a semiconductor material, which excludes electrical carriers having stationary energy states within the band gap, a photonic band gap in a dielectric medium excludes stationary photonic energy states (i.e., electromagnetic radiation having some discrete wavelength or range of wavelengths) within that band gap. In semiconductors, the electronic band gap results as a consequence of having a periodic atomic structure upon which the quantum

mechanical behavior of the electrons in the material must attain eigenstates. By analogy, the photonic band gap results if one has a periodic structure of a dielectric material where the periodicity is of a distance suitable to interact periodically with electromagnetic waves of some characteristic wavelength that may appear in or be impressed upon the material, so as to attain quantum mechanical eigenstates.

A use of these materials that can be envisioned, is the optical analog to semiconductor behavior, in which a photonic band gap material, or a plurality of such materials acting in concert, can be made to interact with and control light wave propagation in a manner analogous to the way that semiconductor materials can be made to interact with and control the flow of electrically charged particles, i.e., electricity, in both analog and digital applications.

Planar photonic crystal circuits such as splitters, high Q-microcavities, and multi-channel drop/add filters have been investigated both theoretically and experimentally in both two- and three-dimensional structures. For two-dimensional photonic crystal structures, the photonic crystal will be either perforated in an infinitely thick dielectric slab or formed of infinitely long dielectric rods. In-plane light confinement is achieved in such structures by multiple Bragg reflections due the presence of the photonic crystal. For three-dimensional photonic crystal structures, confinement in vertical direction is achieved by total internal reflection (TIR).

Work on photonic crystal waveguided components is now moving towards the development of photonic bandgap integrated circuits (PBGICs) in which a variety of active and passive optical components are integrated monolithically on a chip. Electro-optical switches are key components of such PBGICs, yet only one proposal for implementing such switches--a resonator device--has appeared in the literature.

Thus, there is a need in the art for an electro-optical switching device for PBGICs that

addresses the needs of the related art.

SUMMARY OF THE INVENTION

The present invention solves the problems of the related art by providing an optical chip-scale switching using photonic crystals. The switching mechanism is a change in conductance in coupling region between two evanescently coupled photonic crystal waveguides. Conductance is induced electrically by carrier injection or is induced optically by electron-hole pair generation. The present invention provides real time optical signal processing by utilizing optical switching in photonic crystals over a small area which will facilitate future integration with optical integrated circuits.

The present invention provides a new technique for switching an electromagnetic wave propagating through photonic crystal waveguides. Electromagnetic waves can be either in the microwave or optical regime, based upon the constituent materials of a photonic crystal. The invention makes use of coupled photonic crystal waveguides, where the coupling coefficient between nearby waveguides can be modulated via an external electrical or optical means. The present invention proposes that the "loss tangent" of dielectric material in the coupling region can be modified by external "commands" to spoil the coupling, thereby re-routing the light. This is an $\Delta\alpha$ switch (not the classical $\Delta\beta$ switch) in which the change in optical absorption coefficient $\Delta\alpha$ is employed (the change in conductance $\Delta\sigma$ is proportional to $\Delta\alpha$). The present inventors have found that the induced loss does not significantly attenuate the waves traveling in the straight-through channels. To attain switching in two-dimensional ("2D") PBG guides made from silicon (Si)/air or Si/SiO_2, the free-carrier absorption loss of Si can be controlled by: (1) carrier injection from forward-biased PN junctions on the posts; (2) depletion of doped posts

with MOS gates; or (3) generation of electrons and holes by above-gap light shining upon the designated pillars, a non-contact process. If the PBG coupler is implemented in III-V semiconductor heterolayers, then the electro-absorption effect could be used.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein:

Fig. 1 is layout of PBG optical switch and predicted optical intensity distribution within the switch for (a) the Cross state, with low conductivity σ in the coupling region, (b) the Bar state with significant σ induced in the two rows of coupling pillars;

Fig. 2 is a graph showing the calculated switching characteristics of the cross-bar switch shown in Fig. 1; and

Fig. 3 is a graph showing the dependence of σ upon N and P doping.

DESCRIPTION OF EMBODIMENT(S) OF THE PRESENT INVENTION

The following detailed description of the invention refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. Also, the following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims and equivalents thereof.

The present invention presents the conception, modeling and simulation of a PBG channel-waveguided 2 x 2 directional coupler switch that utilizes electrically or optically induced loss (conductivity) in the rows of dielectric pillars between two coupled waveguides. The present invention is the first PBG directional coupler switch that has been proposed and analyzed.

1. Switching Approach

A related technology reports new and practical designs for passive TE-polarized 2D waveguided PBG couplers having $l_c = 48a$, as set forth in **Masanori Koshiba, "Finite Element Analysis of Optical Waveguides," Paper IMD1, *IPR2001* (Monterey, June 11, 2001).** Taking this result a step further, the present inventors propose that the "loss tangent" of dielectric material in the coupling region can be modified by external "commands" to spoil the coupling, thereby re-routing the light. This is an $\Delta\alpha$ switch (not the classical $\Delta\beta$ switch) in which the change in optical absorption coefficient $\Delta\alpha$ is employed (the change in conductance $\Delta\sigma$ is proportional to $\Delta\alpha$). The present inventors have found that the induced loss does not significantly attenuate the waves traveling in the straight-through channels. This behavior is analogous to that discussed in **R. A. Soref et al., "Proposed N-Wavelength M-Fiber WDM Crossconnect Switch Using Active Microring Resonators," *IEEE Photonics Technology Letters*, vol. 10, pp. 1121-1123 (Aug. 1998)**, where electro-absorption was assumed to reduce the Q of micro-ring resonators coupled to strip channel waveguides. To attain switching in 2D

PBG guides made from Si/air or Si/SiO_2, the free-carrier absorption loss of Si can be controlled by: (1) carrier injection from forward-biased PN junctions on the posts; (2) depletion of doped posts with MOS gates; or (3) generation of electrons and holes by above-gap light shining upon the designated pillars, a non-contact process. If the PBG coupler is implemented in III-V semiconductor heterolayers, then the electro-absorption effect could be used. The present distributed-coupling device differs from the conventional PBG switching device (see **U.S. Patent No. 6,101,300**) that relies upon a point-defect resonator, or two point defects, situated between two PBG channels. U.S. Patent No. 6,101,300 assumed that the Q of those cavities would be spoiled by loss induced electrically at the defects.

2. <u>Modeling And Simulation Of Switch</u>

For the 1550 nanometer (nm) center wavelength, it was assumed a 2D photonic crystal of 434 nm diameter silicon dielectric rods ($\varepsilon_r = 11.6$) arrayed in a square lattice ($a = 543$ nm) on an air background. Line defects and bent lines defined the channel waveguides. PBG waveguides of the present invention are analogous to the practical 2D e-beam-etched silicon waveguide system developed by **M. Loncar et al., "Waveguiding in Planar Photonic Crystals,"** ***Applied Physics Letters*, vol. 77, pp. 1937-1939 (Sep. 25, 2000).**

In this analysis, the finite-difference time-domain ("FDTD") method was used with perfectly matched absorbing boundary conditions around the rectangle enclosing the 2x2 switch to truncate the computational domain and minimize reflections from this outer boundary. A full wave solution for forward and backward traveling waves solved alternately for E and H fields at different spatial points ($\lambda/20$ sampling rate) as time progressed. Eight 1-Gbyte/sec personal computers processing in parallel provide solutions. Examination of several switching test structures at $\sigma \sim 0$, showed that the length $l_c = 21a$ of the parallel-channel interaction region

ensured that ~100% of the optical power launched into Port 1 was transferred to the other waveguide. The spectral transmission of this coupler was analyzed and found a periodic response (see Masanori Koshiba, *supra*) whose first peak has a FWHM passband of about 20 nm.

3. **Results**

Fig. 1 presents a top view of the planar "crossbar" of the present invention in its off and on conditions. Top views of the corresponding infrared intensity distributions within the device are also shown. For a given value of σ and assuming unity power input to Port 1, the power emerging from Ports 2, 3, and 4, respectively, was determined. This switching response as a function of σ is shown in Fig. 2. The transmissions are: T(Port 2) > 81% for $\sigma > 30\ \Omega^{-1}cm^{-1}$ and T(Port3) > 88% for $\sigma < 0.0003\ \Omega^{-1}cm^{-1}$. At $\sigma = 10^{-4}\ \Omega^{-1}cm^{-1}$, the predicted crosstalks are: Forward CT= P(2)/P(3) = -29.4 dB; and Backward CT= P(4)/P(3) = -27.3 dB. While for $\sigma = 100\ \Omega^{-1}cm^{-1}$, the predicted crosstalks are: Forward CT=P(3)/P(2) = -23.1 dB; and Backward CT = P(4)/P(2) = -28.6 dB. The Fig. 1 devices are intended to be interconnected and cascaded in the forward direction into an N x N optical cross-connect network. Response similar to that in Fig. 2 is expected for a hexagonal lattice switch. Preliminary calculations show that a two-row switch that has a coupling length 2x or 3x longer than that in Fig. 1 will be more sensitive to conductivity changes than the Fig. 1 device. That is, the swing from Off to On will be produced with a smaller $\Delta\sigma$. If it is assumed that the dielectric posts are undoped "intrinsic" silicon, then to determine what concentrations of electrons or holes are required to be injected into those posts to obtain the desired increase in conductance, it is assumed that the effect of injection is approximately the same as the effect of doping the silicon with n-type or p-type impurities. From Fig. 21of S. M. Sze, ***Physics of Semiconductor Devices*** **(2d ed. 1981)**, the dependence of

σ upon doping density is shown in Fig. 3.

4. Summary

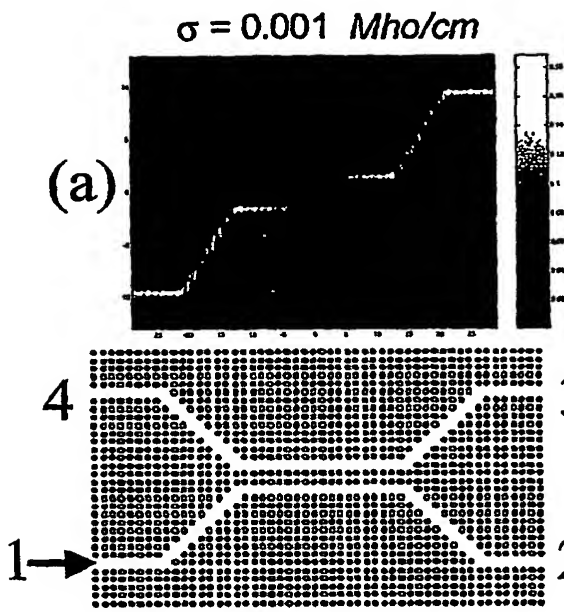
The above description provides simulation results on a novel, compact, TE-polarized 2D PBG waveguided 2x2 directional coupler switch controlled by optical loss induced in the dielectric posts between the parallel line defects in accordance with the present invention. Using the FDTD method on a 1.55 mm device, low insertion loss and crosstalk below -23 dB is predicted in both switching states. The present inventors are presently exploring improved switch designs that produce "complete" switching with smaller $\Delta\sigma$.

It will be apparent to those skilled in the art that various modifications and variations can be made in the electro-optical two-by-two ("2x2") switching in a photonic bandgap waveguided coupler of the present invention and in construction of this device without departing from the scope or spirit of the invention. As an example, the material selections and dimensions discussed above are purely exemplary and not limiting of the present invention.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only.

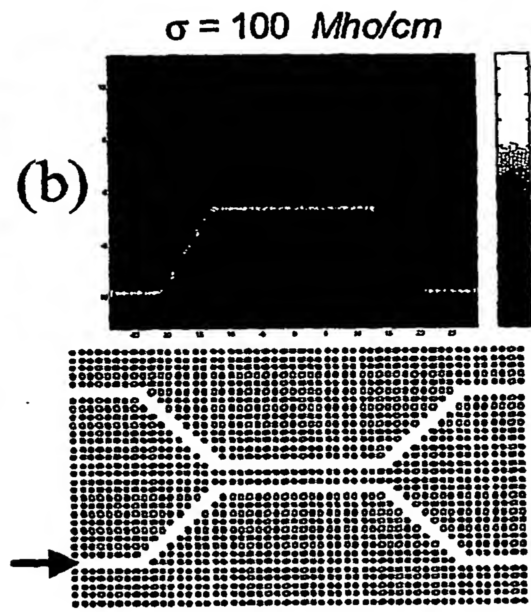
ABSTRACT OF THE DISCLOSURE

A new two-dimensional ("2D") photonic bandgap ("PBG") directional coupler switch is proposed and analyzed by the FDTD method. A 1.55 millimeter (mm) device is designed in a square lattice of silicon posts in air. The switching mechanism is a change in the conductance of posts located in the waveguide coupling region. Conductance is induced electrically by carrier injection or is induced optically by electron-hole pair generation. Low insertion loss and optical crosstalk below -23 dB in both the cross and bar switching states are predicted.



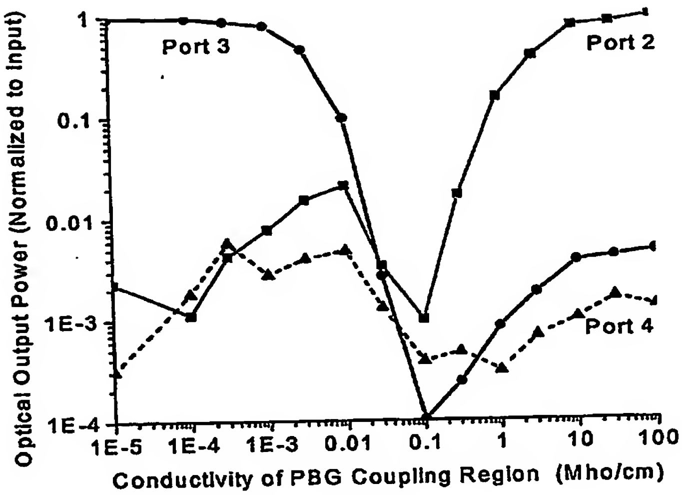
Off state of switch

Fig. 1(a)



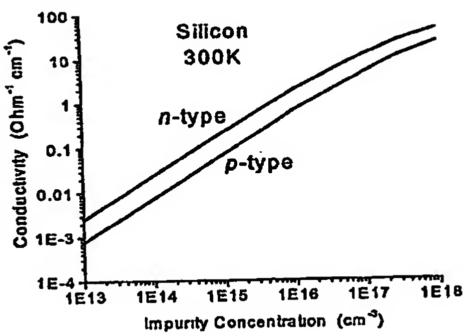
On state of switch

Fig. 1(b)



Optical Output Power (Normalized to Input)
1
0.1
0.01
1E-3
1E-4
Port 3
Port 2
Port 4
1E-5
1E-4
1E-3
0.01
0.1
1
10
100
Conductivity of PBG Coupling Region (Mho/cm)

Fig. 2



Silicon
300K
n-type
p-type
Conductivity (Ohm⁻¹ cm⁻¹)
100
10
1
0.1
0.01
1E-3
1E-4
1E13
1E14
1E15
1E16
1E17
1E18
Impurity Concentration (cm⁻³)

Fig. 3